

AN XMM-NEWTON OBSERVATION OF 4U1755-33 IN QUIESCENCE: EVIDENCE FOR A FOSSIL X-RAY JET

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ABSTRACT

We report an XMM-Newton observation of the Low mass X-ray Binary (LMXB) and black hole candidate 4U1755-33. This source had been a bright persistent source for at least 25 yrs, but in 1995 entered an extended quiescent phase. 4U1755-33 was not detected with an upper limit to the 2–10 keV luminosity of $5 \times 10^{31} d_{4kpc}^2$ ergs s⁻¹ (where d_{4kpc} is the distance in units of 4 kpc) – consistent with the luminosity of other black hole candidates in a quiescent state. An unexpected result is the discovery of a narrow 7 arc min long X-ray jet centered on the position of 4U1755-33. The spectrum of the jet is similar to that of jets observed from other galactic and extragalactic sources, and may have been ejected from 4U1755-33 when it was bright. Jets are a feature of accreting black holes, and the detection of a fossil jet provides additional evidence supporting the black hole candidacy of 4U1755-33. The spectral properties of three bright serendipitous sources in the field are reported and it is suggested these are background active galactic nuclei sources.

Subject headings: stars: individual (V4134 Sagittarii, 4U1755-33) — binaries: close — X-rays: stars

1. Introduction

The LMXB 4U1755-33 had been a permanent feature of the X-ray sky since its discovery in the first all-sky X-ray survey by the Uhuru satellite in 1970 (Giacconi *et al* 1974), with a typical flux of $\sim 100 \mu\text{Jy}$. An observation by *RXTE* in January 1996 revealed that 4U1755-33

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had turned off, with an upper limit to a flux of $\leq 1 \mu\text{Jy}$ (Roberts *et al.* 1996). The *RXTE* all sky monitor shows it has been quiescent since then, to the time of writing. 4U1755-33 has an orbital period of 4.4 hr, which was established from regular periodic dipping in the X-ray lightcurve (White *et al.* 1984), and confirmed in photometric variations in the 18–19 magnitude optical counterpart V4143 Sagittarii (Mason, Parmar and White 1985). Since the X-ray source turned off, the optical counterpart has become fainter than $V > 22$ (Wachter and Smale 1998).

When it was active 4U1755-33 was noted for having an ultrasoft X-ray spectrum, similar to that of black hole candidates (White and Marshall 1984, White *et al.* 1984). The spectral evidence for the compact object being a black hole was further strengthened when broad band observations revealed a hard X-ray tail, again similar to that seen in other black hole systems (Pan *et al.* 1995). However, the possibility that a neutron star might mimic this spectral signature could not be ruled out (see e.g. Seon *et al.* 1995 and references therein).

The study of LMXBs during quiescence, when the luminosity is a factor of 1 million or more fainter than the peak, has become an important tool to investigate the nature of the compact object and the physics of the accretion process (see e.g. Garcia *et al.* 2000). Observations with ASCA, Beppo-SAX and ROSAT were the first to detect faint emission from these LMXBs in quiescence with a luminosity of typically $\leq 10^{32}$ ergs s^{-1} with fluxes of $\leq 10^{-14}$ ergs cm^{-2} s^{-1} (e.g. Menou *et al.* 1999). What were once the brightest X-ray sources, have become among the faintest. The luminosity of systems thought to contain a black hole appears to be significantly fainter than systems thought to contain a neutron star (e.g. Menou *et al.* 1999). This lower luminosity of the black hole systems has been attributed as due to the lack of a solid surface on the compact object and used as supporting the existence of the black hole event horizon (e.g. Garcia *et al.* 2000). These systems are also used to test models for the accretion disk emission e.g. the Advection Dominated Accretion Flow (ADAF) model (Narayan, McClintock and Yi 1996).

With the advent of XMM-Newton and *Chandra* it is possible to extend these studies using more sensitive observatories. Many such programs are underway to increase the number of systems studied and also to test in more detail the accretion disk models (e.g. Hameury *et al.* 2002). In this paper we present the results of an observation of 4U1755-33 in its quiescent state using the European Space Agency's XMM-Newton Observatory (Jansen *et al.* 2001).

2. Results

2.1. The Observation

4U1755-33 was observed by the XMM-Newton observatory on March 3, 2001 starting at 05:13 hr UT and ending at 10:30 hr. XMM-Newton has three X-ray telescopes with two different types of CCD arrays in each focal plane. Two CCD cameras use MOS arrays and one a PN array. The data were processed using XMM-Newton Science Analysis System (SAS) version 5.3.3. Images were accumulated from the cleaned event files selecting good events as recommended in the users guide. Images were made for each CCD camera in the 0.5–4.5 keV band, 6.2–6.8 keV iron band and 0.5–10 keV band. The good time exposure in each camera was: MOS-1=18127s, MOS-2=18107s and PN=15359s.

The three images in the 0.5–4.5 keV band were summed together and the total image is shown in Figure 1. The position of 4U1755-33 is at the center of the image, and is marked with a circle. While many sources are seen in the image, there is none at the position of 4U1755-33. A striking aspect of the image is a ~ 7 arc min long jet-like feature of extended emission that passes through the position of 4U1755-33. There are several bright spots embedded in the extended emission, in particular on the southern side.

To examine the region around 4U1755-33 in more detail in Figure 2 we show the individual images from the PN camera and the summed MOS cameras for the 0.5–10 keV band. The lower two images zoom in on the position of 4U1755-33. We separate the MOS and PN cameras so that the gaps in the image caused by CCD chip boundaries or bad columns can be seen. The position of 4U1755-33 is marked on the PN image.

2.2. 4U1755-33 in Quiescence

An upper limit to the flux from 4U1755-33 was obtained by selecting an optimum sized region around the source. A circle of radius 7 arc sec was used to minimize the contribution from the extended emission, this includes about 45% of the telescope point spread function (PSF). Because of the different energy response of the two types of CCD cameras and different coverage across the CCD we separately estimated an upper limit for the summed MOS and the PN images. By taking many different backgrounds across the image an average background count rate was estimated and found to be similar to the count rate at the position of 4U1755-33.

A three sigma upper limit was derived from the count rate in the source box using the statistics method described by Gehrels (1986). The upper limits derived for the summed

MOS and PN are $< 3.4 \times 10^{-4}$ count/s and $< 1.3 \times 10^{-3}$ count/s in the 0.5–2 keV and $< 3.5 \times 10^{-4}$ count/s and $< 1.4 \times 10^{-3}$ count/s in the 2–10 keV bands. This was then corrected by a factor of 2.2 to correct for the portion of the telescope point spread function not included in the circle.

The corresponding flux level depends on the assumed spectrum. When active the spectrum of 4U1755-33 had a characteristic temperature of ~ 2 keV and an equivalent hydrogen column density of 5×10^{21} cm $^{-2}$ (White *et al.* 1984). The distance to 4U1755-33 is very uncertain with estimates ranging from 4 to 9 kpc (see Wachter and Smale 1998). Table 1 summarizes the various flux upper limits for the MOS and PN, using the given range of distance and two temperatures of 2 and 10 keV. The latter temperature is representative of other transient black hole systems detected in quiescence (e.g. Narayan *et al.* 1996). These upper limits are corrected for any attenuation by interstellar absorption. The MOS gives the most restrictive upper limits, which for the 2–10 keV band corresponds to $3.6 \times 10^{31} d_{4kpc}^2$ ergs s $^{-1}$ (where d_{4kpc}^2 is the distance in units of 4 kpc) assuming a 10 keV spectrum.

The ratios of the quiescent luminosity to the peak luminosity and the Eddington luminosity are other useful parameters to compare the relative activity across systems (e.g. Menou *et al.* 1999). This has been applied to transient systems, where there is well defined peak luminosity. For a steady source such as 4U1755-33 it is less clear that this is a meaningful parameter.

2.3. Extended Emission

The extended streak of emission centered on 4U1755-33 is suggestive of a two-sided jet ejected from this X-ray binary when it was active. Profiles along the extended emission were made by slicing the MOS image along the jet-like feature, and for comparison also along an offset position. These are shown in Figure 3 (the regions used are indicated in Figure 2). The bright point source seen passing through the lower slice gives a reference as to the size of the XMM-Newton telescope point spread function (PSF). The bright knots on the left side of 4U1755-33 appear somewhat broader than the PSF of the telescope, suggesting that they are not point sources.

Spectra were extracted from the MOS detectors for two different sized regions along the extended feature, centered on the position of 4U 1755-33, as indicated in Figure 2. A background spectrum was accumulated from a source free region parallel to the jet. The summed MOS spectra were fit to a number of different models: power law, thermal bremsstrahlung and a MEKAL plasma model. The statistics are poor and an acceptable fit is found for all

three models. The PN camera has less uniform coverage because of gaps between the CCDs and bad columns, and was not used for the larger region.

For the inner region the best fit is a photon index of 1.9 ± 0.9 with an equivalent Hydrogen column density of $0.1 \pm_{0.1}^{2.5} \times 10^{21} \text{ cm}^{-2}$ or if the column density is fixed to be $3 \times 10^{21} \text{ cm}^{-2}$, the interstellar value in that direction predicted from the HI map by Dickey & Lockman (1990), the photon index is 2.6 ± 0.7 . The bremsstrahlung and MEKAL models are poorly constrained with $kT > 0.7 \text{ keV}$ and $> 1.7 \text{ keV}$ respectively, even when the absorption is fixed at the interstellar value. Fitting together the MOS and PN spectra for this region give similar and consistent spectral fits. The summed MOS spectrum from the larger region gives a power law photon index of 1.5 ± 0.4 with an absorption of $0.15 \pm_{0.11}^{0.15} \times 10^{21} \text{ cm}^{-2}$ or if the absorption is fixed at the interstellar value gives a photon index of 1.8 ± 0.3 . The best fit bremsstrahlung model for the larger region gives a $kT > 4 \text{ keV}$. In Figure 4 the sum of the MOS spectra for the larger region is shown with the best fitting power law model for the inner region. There is a suggestion that the spectrum of the larger region has a high energy excess, perhaps from contaminating unresolved sources.

2.4. Bright Serendipitous Sources

There are many faint sources in the field, that previously would have been hard to detect when the bright X-ray binary was active, because of scattering in the telescopes.

Three of these field sources stand out in the iron band image and these are indicated with circles in Figure 2. To investigate these sources we extracted PN spectra (because this detector has a harder response). The three spectra are shown in Figure 5. They are quite different, with source 1 (R.A.(J2000)= $17^h59^m00^s.8$ Dec(J2000)= $-33^\circ45'48''.5$) displaying a prominent iron K line, source 2 (R.A.(J2000)= $17^h57^m58^s.7$ Dec(J2000)= $-33^\circ46'26''.5$) a steeper featureless spectrum and source 3 (R.A.(J2000)= $17^h59^m21^s.6$ Dec(J2000)= $-33^\circ53'14''.3$) showing strong absorption. We summarize the spectral fits to a power law model in Table 2.

Three sources were previously detected from ROSAT observations, when 4U1755-33 was active and they are marked in Fig 2 with squares. These three ROSAT sources were the brightest sources after 4U1755-33 reported in the WGACAT ROSAT source catalog for this field (1WGA J1758.6-3341, 1WGA J1758.8-3341 and 1WGA J1759.3-3350). There were about eight other fainter detections reported in WGACAT that do not appear in the XMM-Newton image – we ascribed these to false detections generated by the scattered light from 4U1755-33.

Two of the three new "iron band" sources in the XMM-Newton image are absorbed

and would not have been detected by ROSAT which had a soft < 2 keV spectrum. Source 2 should have been detected by ROSAT and examining the ROSAT PSPC field there is a faint source at this position with a 0.1–2 keV band count rate of ~ 0.005 ct/s, consistent with that predicted.

The *ASCA* source counts (e.g. Kushino *et al.* 2002) predict in the 2–10 keV band 10 sources per square degree $> 10^{-13}$ ergs cm^{-2} s^{-1} . The XMM-Newton field of view covers ~ 0.25 square arc min, so 2–3 extragalactic sources above this flux is consistent the observation of 3 sources. While perhaps one of these sources might be galactic, it seems likely that at least two and probably all three are background active galactic nuclei (AGN).

3. A Fossil Jet from 4U1755-33

The XMM-Newton image of the region surrounding 4U1755-33 reveals a 7 arc minute long jet-like structure, centered on the position of the LMXB. This is very suggestive that the jet was ejected from 4U1755-33 when it was X-ray active. 4U1755-33 is located at $l=357^\circ$ and $b=-4.8^\circ$, i.e. well off the galactic plane. The X-ray dipping seen from this source indicate it is observed close to the orbital plane and so the jets would be expected to be symmetric, as observed. The jet runs at an angle of $\sim 70^\circ$ to the galactic plane, so it is unlikely to be associated with the galactic ridge.

Another possibility is that the emission is a scattering halo from dust intervening between the source. To produce such a narrow ridge would require a rather unusual geometry for the intervening material. The spectrum of a scattering halo would have a spectral index steeper by unity than that of the source (Xu, McCray & Kelley 1986). The spectrum of 4U1755-33 when it was active was very steep, with an equivalent photon index of order 4 (White *et al* 1984) – the opposite of that observed in the extended emission.

X-ray emission from jets has been observed by the *Chandra* X-ray observatory from many black hole systems, both galactic and extra-galactic. The spectra of these jets are typically power laws with a photon index ranging from $\sim 1.5 - 2.2$ (e.g. Kaaret *et al.* 2002; Siemiginowska *et al* 2002; Wilson and Yang 2002), suggesting that non-thermal processes dominate. However, the jet from SS433 shows line emission indicating a hot gas with a temperature of 10^7 to 10^8 K. This should adiabatically cool along the jet (e.g. Brinkmann *et al* 1991), which is not seen from the 4U1755-33 jet, although recent *Chandra* observations demonstrate reenergization of the SS433 jet maybe possible (Migliari, Fender & Mendez 2002).

The quality of the 4U1755-33 jet spectra is not high enough to distinguish thermal or

non-thermal models. When fit with a power law the 4U1755-33 jet has a photon index of 1.5 to 1.9, consistent with that measured from other galactic and extra-galactic jets. The knots in the 4U1755-33 jet are also very reminiscent of similar features seen in other X-ray jets (e.g. Wilson and Yang 2002). If 4U1755-33 is at a distance of 4 kpc, then a 3.5 arc min long jet corresponds to 4 pc. If the jet has a velocity of close to the speed of light, then it would take ~ 13 yr to expand to this length – consistent with the > 25 yr active phase of 4U1755-33. If the jet is no longer being fed since the source has been quiescent, then we might expect to see the central region to be dimmer, and indeed there is some evidence for a hole in the region centered on 4U1755-33 (Figure 1).

4. Discussion & Conclusions

The XMM-Newton observation reported here did not detect any quiescent emission from 4U1755-33. The upper limit to the source luminosity depends on the assumed spectrum and distance. If the source is at the lower end of the assumed ranges (a distance of 4 kpc and temperature of 2 keV) then the upper limit of $\sim 10^{31}$ ergs s^{-1} is comparable to other black hole transients in quiescence with similar orbital periods (Lasota and Hameury 1998; Narayan, Garcia and McClintock 2002), which would strengthen the black hole candidacy of 4U1755-33. If the distance is as far as 9 kpc and the underlying spectrum ~ 10 keV, then the upper limit to the luminosity of $\sim 10^{32}$ ergs s^{-1} starts to overlap the area where both neutron stars and black holes accreting at low accretion rates are found (see Figure 4 in Lasota and Hameury 1998).

The transition of 4U1755-33 into a quiescent state has allowed the surrounding region to be studied in detail. A number of serendipitous sources are detected, some of which may be background AGN. The most surprising result from this observation has been the detection of a faint extended X-ray jet that appears to have been ejected from the source when it was active. Jets are a common feature of black hole candidates in our galaxy and in AGN. The detection of this fossil jet from 4U1755-33 in quiescence provides more circumstantial evidence that 4U1755-33 contains a black hole. The several parsec extent of the jet is consistent with a source that has been active for more than 25 yrs. Confirmation that this is a jet from 4U1755-33 may come from radio observations of the same region. Evidence for a hole in the jet close to 4U1755-33. This may be the first sign that the jet is no longer being replenished – future observations may reveal this hole is expanding.

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6. References

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Table 1: Flux & Luminosity upper limits

Instrument	Temperature keV	Flux		Luminosity	
		0.5-2 ergs cm ⁻² s ⁻¹	2-10 ergs cm ⁻² s ⁻¹	0.5-2 ergs s ⁻¹	2-10 ergs s ⁻¹
MOS	2	9.0×10^{-15}	1.2×10^{-14}	$1.7 \times 10^{31} d_{4kpc}^2$	$2.3 \times 10^{31} d_{4kpc}^2$
PN	2	1.2×10^{-14}	1.8×10^{-14}	$2.3 \times 10^{31} d_{4kpc}^2$	$3.5 \times 10^{31} d_{4kpc}^2$
MOS	10	9.0×10^{-15}	1.9×10^{-14}	$1.7 \times 10^{31} d_{4kpc}^2$	$3.6 \times 10^{31} d_{4kpc}^2$
PN	10	1.2×10^{-14}	2.6×10^{-14}	$2.2 \times 10^{31} d_{4kpc}^2$	$5.0 \times 10^{31} d_{4kpc}^2$

Table 2: Spectral Parameters of the Serendipitous XMM-Newton Sources

Source	Index	N_H 10^{22} cm^{-2}	Absorbed Flux			Line	
			0.5-2 $\text{ergs cm}^{-2} \text{ s}^{-1}$	2-10 $\text{ergs cm}^{-2} \text{ s}^{-1}$	5-10 $\text{ergs cm}^{-2} \text{ s}^{-1}$	Energy keV	EQW eV
1	$1.71 \pm_{0.23}^{0.27}$	$0.96 \pm_{0.25}^{0.37}$	4×10^{-14}	3.17×10^{-13}	1.8×10^{-13}	$6.20 \pm_{0.16}^{0.2}$	876
2	2.08 ± 0.27	$0.32 \pm_{0.07}^{0.13}$	5.6×10^{-14}	1.26×10^{-13}	5.4×10^{-13}		
3	1.7^a	$13.7 \pm_{4.11}^{5.8}$	4.8×10^{-17}	2.8×10^{-13}	2.2×10^{-13}		

^a Power law index kept fixed